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Prediction Unconfined Compressive Strength for Different Lithology Using Various Wireline Type and Core Data for Southern Iraqi Field

Worood Al-Zubaidy[1],*, Mohammed Al-Jawad[2]

Department of Petroleum Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
engineerworood1989@gmail.com[1], mjawad@coeng.uobaghdad.edu.iq[2]

ABSTRACT

Unconfined Compressive Strength is considered the most important parameter of rock strength properties affecting the rock failure criteria. Various research have developed rock strength for specific lithology to estimate high-accuracy value without a core. Previous analyses did not account for the formation's numerous lithologies and interbedded layers. The main aim of the present study is to select the suitable correlation to predict the UCS for hole depth of formation without separating the lithology. Furthermore, the second aim is to detect an adequate input parameter among set wireline to determine the UCS by using data of three wells along ten formations (Tanuma, Khasib, Mishrif, Rumaila, Ahmady, Maudud, Nahr Umr, Shuaiba and Zubair). After calibration with core test, the results revealed that Young's Modulus correlations are the best to predict UCS with RMSE (53.23 psi).
Furthermore, the result showed that using the static Young Modulus as an input parameter in predicting UCS gives a closer result to the laboratory test than using a sonic log. This study found that many previous equations were developed for only one type of rock and tended to generalize poorly to the broader database. This study also provided more accurate rock strength estimation, leading to better prognosis in operational strategies and hydraulic fracturing location planning in oil well development when geomechanical analysis needs to be addressed where no core is available. Finally, the expected continuous rock mechanical profile indicates the formation's strength and stability around the wellbore.

Keywords: Un-confined compressive strength**,** Lithology, Wireline, Core data.

*Corresponding author
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التنبؤ بقوة الانضغاط غير المحصورة لأنواع مختلفة من الصخور باستخدام مجسات متنوعة وفحوصات اللباب لحقل في جنوب العراق

ورود عبد العباس حسن[1]،*، محمد صالح الجواد[2]

قسم هندسة النفط ، كلية الهندسة، جامعة بغداد، بغداد، العراق

الخلاصة

تعتبر قوة الانضغاط الغير محصورة من اهم خصائص مقاومة الصخور التي تؤثر على معيار انهيار الصخور. اجريت العديد من الدراسات لتطوير التنبؤ بتلك الخاصية والحصول على حسابات دقيقة في غياب الفحوصات المختبرية. الدراسات السابقة كانت تتناول نوع محدد من الصخور ولم تأخذ بنظر الاعتبار ان التكوينات الجيولوجية تكون معقدة التركيب وتتألف من عدة انواع من الصخور التي تكون غالبا متداخلة مع بعضها بشكل طبقات متتابعة يصعب فصلها. الهدف الاساسي من هذه الدراسة هو تحديد المعادلة المناسبة لحساب قوة الانضغاط الغير محصورة للعمق الكامل للتكوين بإهمال نوع الصخرة, بالإضافة الى ذلك تحديد اي نوع من المجسات او الخواص الميكانيكية التي تعطي تنبؤ جيد لقوة الانضغاط الغير محصورة باستخدام بيانات ثلاث آبار ولعشرة تكوينات (تنومه, الخصيب, المشرف, الرميلة, الأحمدي, مودود, نهر عمر, الشعيبة, الزبير). اظهرت النتائج وبعد المطابقة مع الفحوصات المختبرية ان معادلة يونك هي الأكثر واقعية واعطت مقدار خطأ حوالي (53.23 psi), بالإضافة الى ذلك فأن استخدام معامل يونك لحساب قوة الانضغاط الغير محصورة هو الاقرب من القيم المختبرية على العكس من استخدام مجسات سرعة الصوت التي اعطت قيم بعيدة جدا.

في هذه الدراسة وجد ان العديد من المعادلات السابقة تم تطويرها لنوع محدد من الصخور وعند استخدامها للتعميم سوف تعطي نتائج خاطئة. قدمت هذه الدراسة ايضا تقدير اكثر دقة لقوة الصخور مما يؤدي الى تشخيص افضل في الاستراتيجيات التشغيلية وتخطيط موقع التكسير الهايدروليكي في تطوير آبار النفط عندما يحتاج النموذج الجيوميكانيكي الى معالجه عند عدم توفر الفحوصات المختبرية. واخيرا" فأن ايجاد العمود المستمر للخواص الصخرية يعتبر مؤشر جيد لقوة واستقرار التكوين حول جدار البئر.

الكلمات المفتاحية: قوة الانضغاط غير المحصورة, نوع الصخرة, مجسات تخطيط الآبار, بيانات اللباب.

1. INTRODUCTION

The Uniaxial Compressive Strength (UCS) and elastic characteristics of rocks, such as Young's modulus and Poisson's ratio, are extensively used to estimate in situ stresses, wellbore stability study, reservoir compaction survey, and prediction of optimal drilling mud pressure **(Chang et al., 2006; Abdulraheem et al., 2009)**. Rocks' Elastic characteristics are assessed using dynamic and static techniques, while UCS is exclusively determined using the static technique **(Al-Shayea, 2004)** and core test. In the dynamic technique, compressional and shear wave velocities may be recorded in the lab or the field, and elastic characteristics can be computed appropriately. Empirical correlations have been presented to solve the

problem of inferring mechanical parameters from wireline data **(Edimann et al., 1998; Ameen et al., 2009; Ranjbar-Karami and Shiri, 2014)**. These correlations estimate porosities or acoustic velocities by empirically correlating laboratory-derived rock mechanical characteristics with geophysical well logs **(Hassan and Hussien, 2019)**. Many elements that impact rock mechanical characteristics also affect porosity, velocity, and elastic moduli underlies these correlations **(Chang et al., 2006)**. To predict the UCS value when no core is available for laboratory testing, several notable previous publications studied the relationship between the UCS with the well log properties for specific formations and geological settings, creating different UCS equations at specific settings **(Abed and Hamd-Allah, 2019; Aziz and Hussein, 2021a; Aziz and Hussein, 2021b)**. Many empirical correlations estimate rock mechanical characteristics using geophysical logging data **(Ryshkewitch, 1953)**. Case studies of geological features globally yielded these connections. Rock mechanical profiles may be accurately and efficiently obtained by correlating porosity with several rock mechanical characteristics. According to **(Hoshino, 1974)** rock strength and elasticity depend on porosity. **(Kowalski, 1975; Sethi, 1981)** proposed porosity wireline logs for rock strength parameters. **(Vernik et al., 1993)** calculated unconfined compressive strength from porosity for sedimentary basins globally, especially for highly clean, well-consolidated sandstones with porosity < 0.3. **(Sarda et al., 1993)** identified a straightforward empirical relationship between rock porosity and unconfined compressive strength. The relationship was discovered using laboratory research on sandstone core samples from the Germigny-sous-Coulombs structure in France. **(Edimann et al., 1998)** employed core-measured porosity and rock mechanical parameters for North Sea sandstone samples to determine direct linear correlations between them and estimate the continuous rock mechanical profile. **(Horsrud, 2001)** used the power law function to suggest North Sea Tertiary shale transit time and UCS connection. **(Chang et al., 2006)** synthesized UCS and acoustic transit time data for worldwide, Gulf of Mexico, and Pliocene and younger shale. **(Onyia, 1988)** estimated the UCS from well logs for shale, sandstone, limestone, dolomite, granite, and mixed lithologies. **(Horsrud, 2001)** developed the UCS estimation from compressional wave velocity for the North Sea area. Hareland and Nygaard (2007) developed the equation for calculating the UCS from sonic transit time for sandstone, shale, and mixed lithologies for onshore United Kingdom, offshore North Sea, and Norwegian Sea. The studied interval passes through complex formations (these formation contain limestone, dolomite, sandstone interbedded with beds of shale. The main advantage of the present study is to find suitable correlation to predict the UCS for longer well section, then, the operational cost can be decreased by minimizing the need to conduct core operations and laboratory measurements.

In this study, many previous correlations are applied to the data of the three wells. Then, the results are calibrated with the core data. Finally, statistical analysis is done to detect the suitable correlation to get a good match with laboratory tests and can be used to estimate the UCS for the total depth of complex formations regardless of the lithology.

2. AVAILABLE DATA

All data in this work are collected from the Southern Iraqi oilfield. The data includes geophysical logging and mechanical properties and focuses on formations consisting of complex lithology (ex, shale interbedded with sandstone or limestone)**(Neeamy and Selman, 2020)**. The lithology description for studied wells is illustrated in **Fig. 1**, while **Fig. 2 to 4** describes the available logs for each well.

Age		Group	Formation	Lithology	Description	Average thickness (m)
Period	Epoch					
Tertiary	L. Miocene-Recent	Kuwait	Dibdibba		Sand & pebble	200
	Early-M Miocene		Lower fars		Clay St, Lst arg	170
			Ghar		Sand & subround pebble occ Clay	110
	M-L Eocene	Hasa	Dammam		Dolomite, porous vuggy	210
	Paleocene –Early Eocene		Rus		Anhydrite,white, massive Interbedded w\ Dolomite	165
			Umm-Er-Radhuma		Dolomite grey saccharoidol, inpart anhydritic	450
Cretaceous	Late Cretaceous	Aruma	Tayarat		Bituminous Shale at top, Dolomite, grey	220
			Shiranish		Limestone marly	120
			Hartha		Lst,gloc,Dol,porous,locally vuggy,Lst,grey ,arg.	180
			Sadi		Limestone white, chalcky, fine, compact	260
			Tanuma		Shale: black-brown fissile	50
			Khasib		Limestone: grey shaly	45
	Middle Cretaceous	Wasia	Mishrif		Limestone: white detrital, porous, rudist	150
			Rumaila		Limestone:, grey, marly	100
			Ahmadi		Shale: Dark grey, fissile w/ Limestone: grey	140
			Mauddud		Limestone grey	110
			Nahr Umr		Shale black inter. w/ Sst	270
	Early Cretaceous	Thamama	Shuaiba		Lst , Dolmaite fracture	85
			Zubair		Shale,fissile, w/ sandstone fine-m. grained, Silt st, Clay st.	400
			Ratawi		Limestone with streaks of Shale	200
			Yamama		Limestone, light grey	120
Jurassic	UpperJurassic		Sulaiy		Limestone, argillaceous and marly	300

Figure 1. Lithology description for Southern Iraqi Fields **(INOC, 1979)**

In this study, three wells are used for UCS prediction analysis, these are X1, X2, and X3. There are core tests available in Tanumma, Mishrif, Nahr Umr, and Zubair formations. **Table 1.** Summarizes the well data used in this study.

Table 1. Well data summary.

Well Name	Data				
	Well Logs			Static Rock Properties	Core Data
	Density Log	Sonic Log	Effective Porosity		
X1	Available	Available	Available	Not Available	Available
X2	Available	Available	Available	Not Available	Available
X3	Available	Available	Available	Not Available	Available

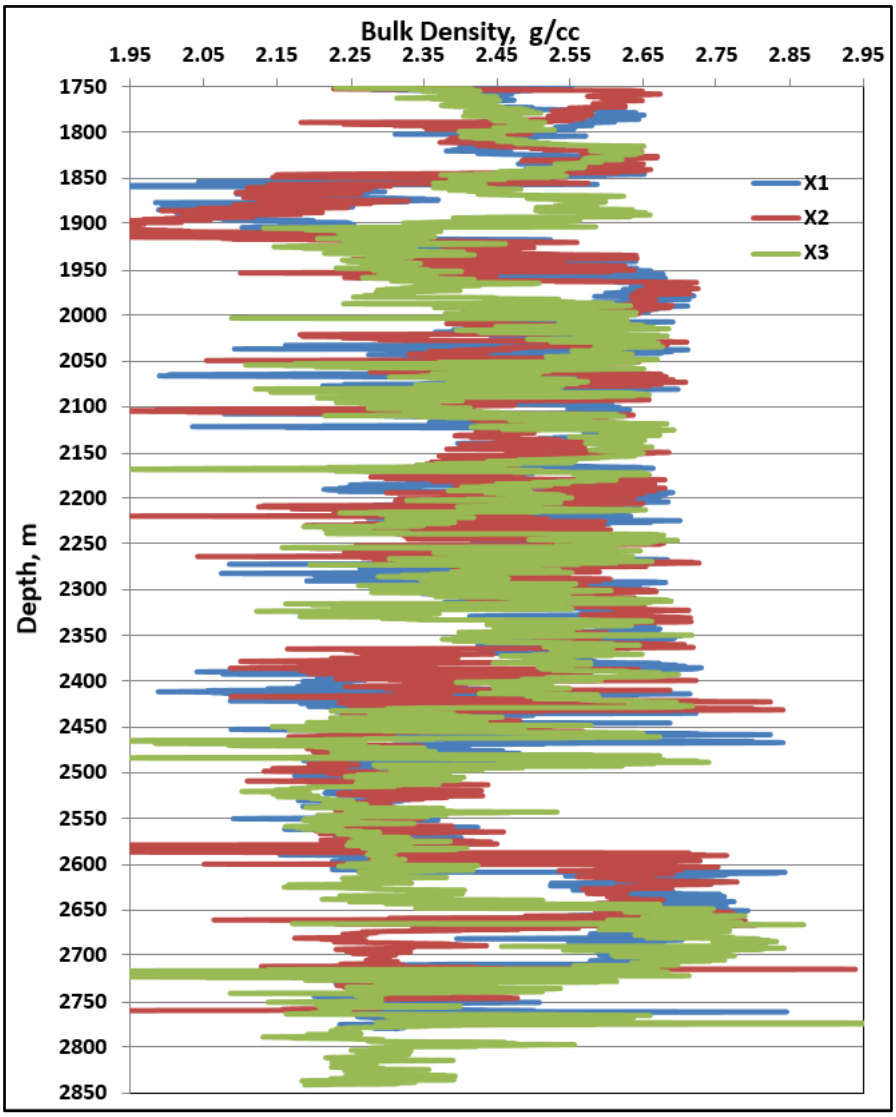

Figure 2. Bulk density graph for studied wells.

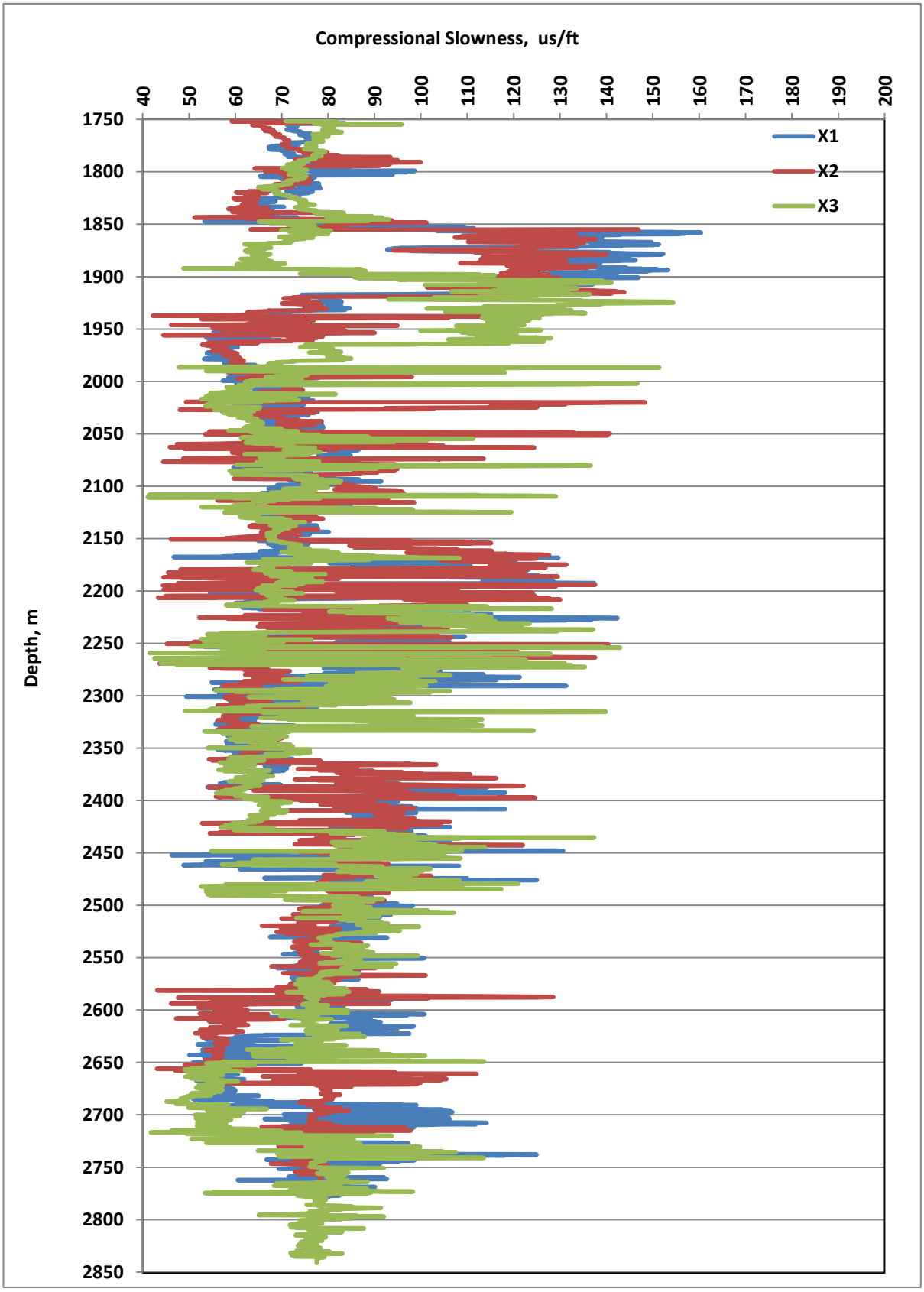

Figure 3. Compressional Wave Velocity for studied wells.

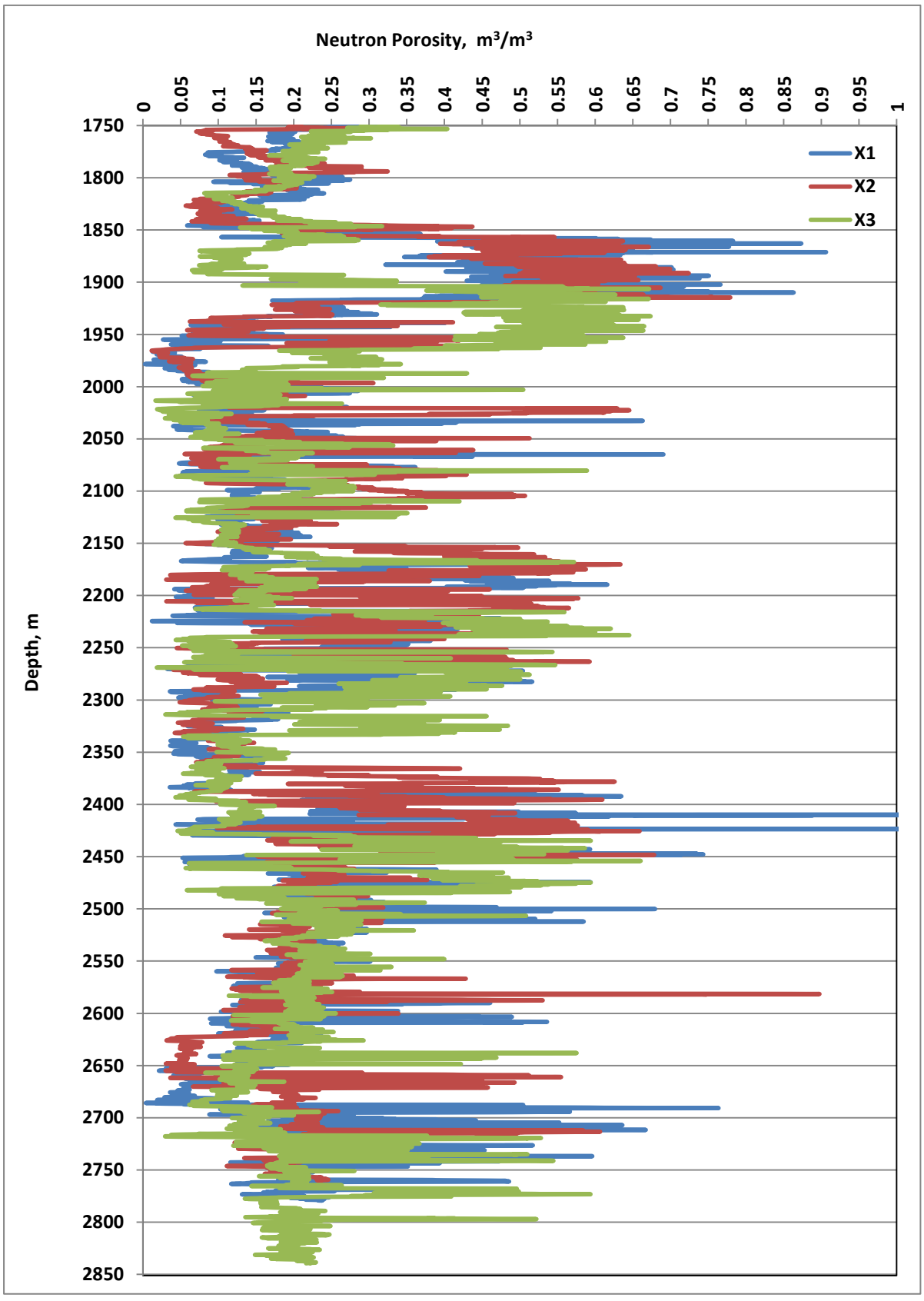

Figure 4. Neutron Porosity graph for studied wells.

3. METHODOLOGY

- Following the identification of all essential and usable data files, non-ASCII files were changed to ASCII files utilizing free software.
- The next step was to create a plot of the data to assess its accuracy.
- Once the log data has been loaded, rock may start doing property calculations.
- Estimate Dynamic and Static Young's Modulus.
- Several models have been investigated to predict UCS by using Excel program **(Coates Denoo, 1963; McNally, 1987; Vernik et al., 1993; Plumb, 1994; Bradford et al., 1998; Moos et al., 2003; static Young's, 2002; Savitri et al., 2021)**.
- Calibration has been performed between the results and lab test data.
- Statistical analysis was used to detect which correlation gives a good match with core test.

Flowchart for building the model using Excel illustrated in **Fig. 5**.

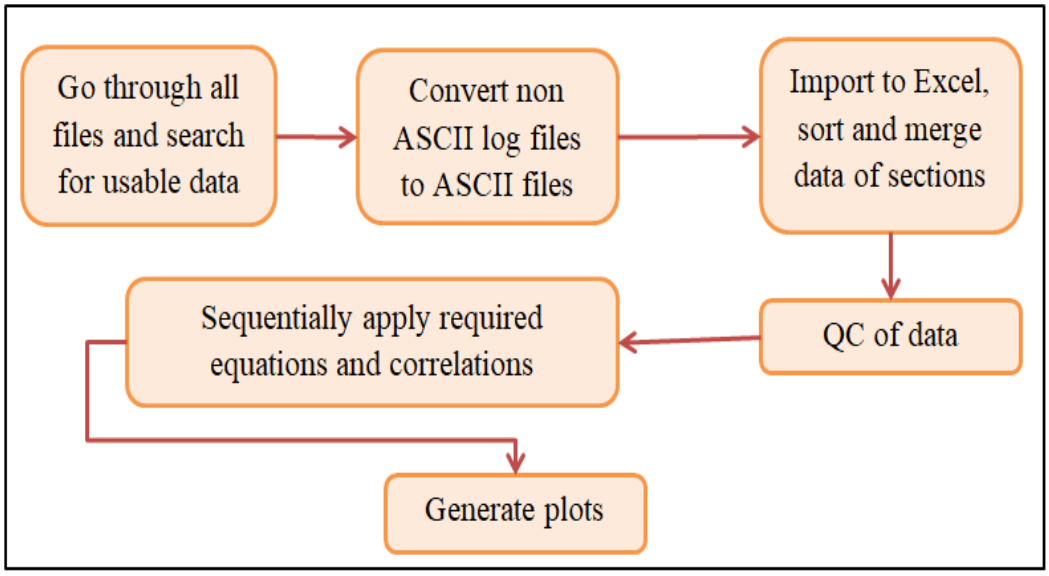

Figure 5. Flowchart for building the model using Excel.

4. RESULT AND DISCUSSION

4.1 Determination of Dynamic and Static Young's Modulus

Young's modulus is the stiffness degree of the rock **(Fjær et al., 2021; Ahmed and Al-Jawad, 2020)**. Hooke's law defines the rules for the linear relationship that exists between stress (σ) and strain (ϵ)**(Allawi and Al-Jawad, 2021a)**. Some correlations to predict UCS depend on Young's Modulus, so the equations below are applied to predict the Young Modulus value. **Figs. 6 to 8** illustrate the results of Static Young's Modulus, which was calculated by Eq. 2 and appears to match laboratory tests.

$$E_{dyn} = \frac{9G_{dyn}K_{dyn}}{G_{dyn} + 3K_{dyn}} \quad (1)$$

$$E_{static} = 0.032 \times {E_{dyn}}^{1.632} \quad (2)$$

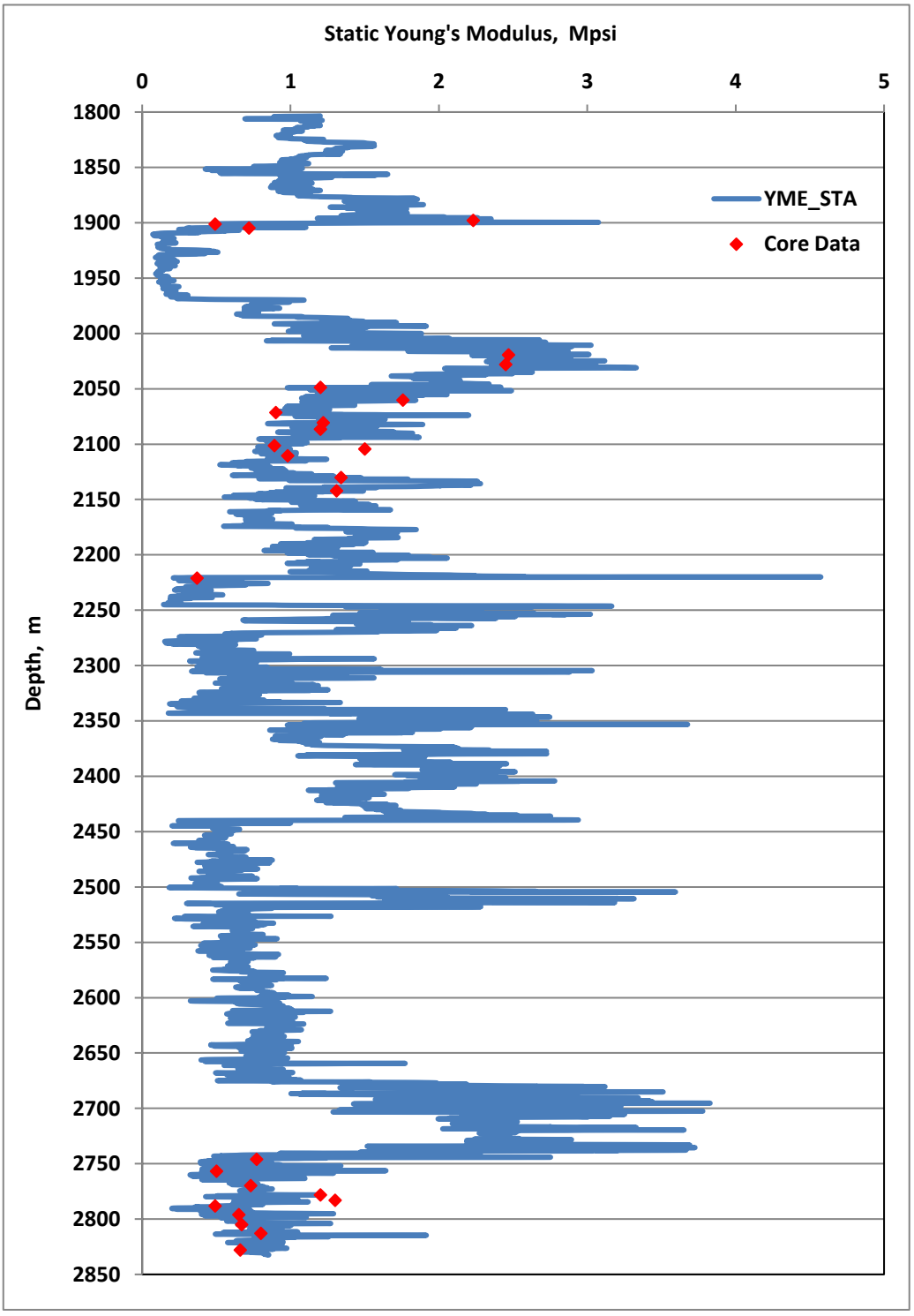

Figure 6. Static Young Modulus for well X1.

where:

$$G_{dyn} = 13474.45 \frac{\rho_b}{(\Delta t_s)^2} \quad (3)$$

$$K_{dyn} = 13474.45 \frac{\rho_b}{(\Delta t_c)^2} - \frac{4}{3} G_{dyn} \quad (4)$$

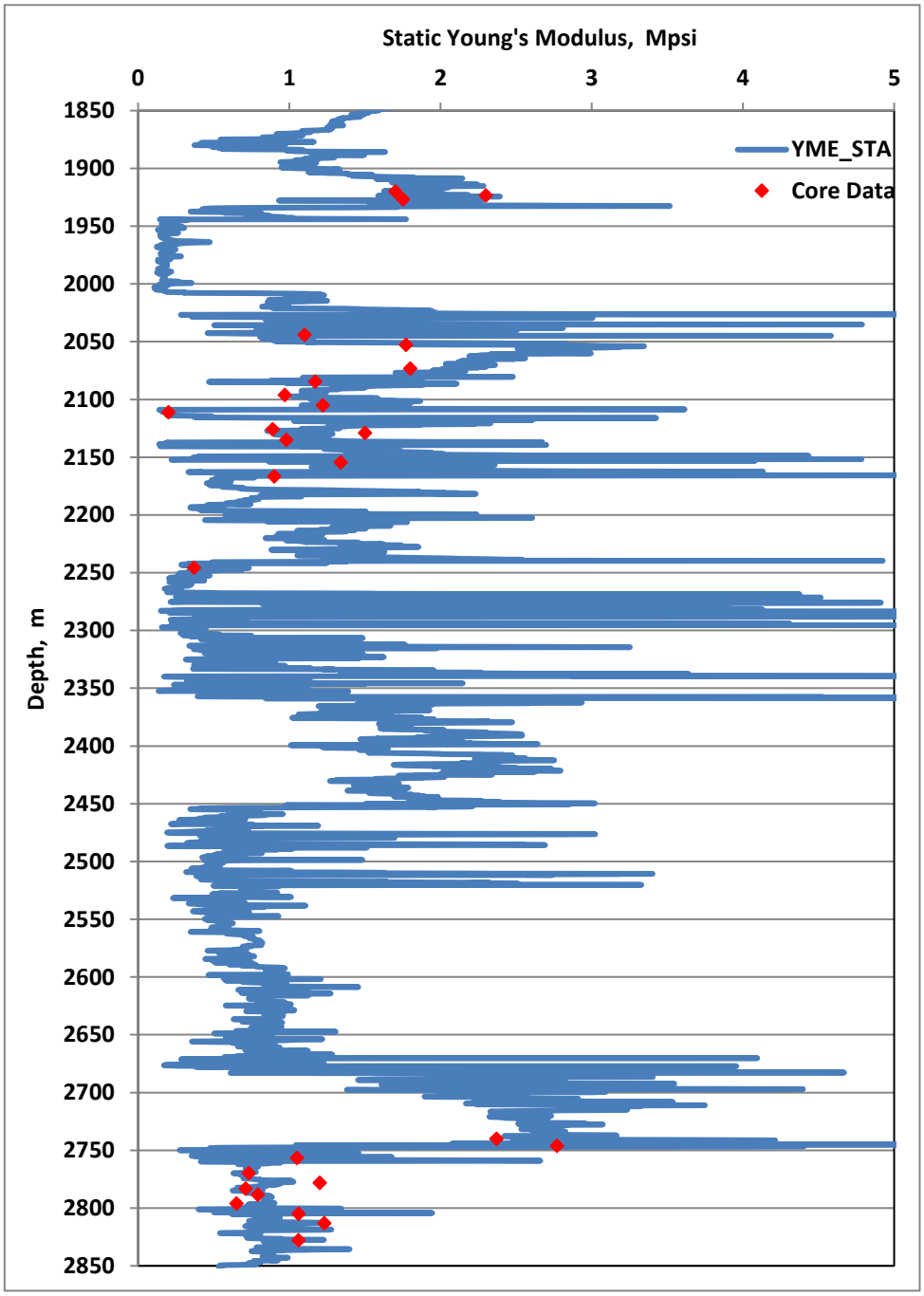

Figure 7. Static Young Modulus for well X2.

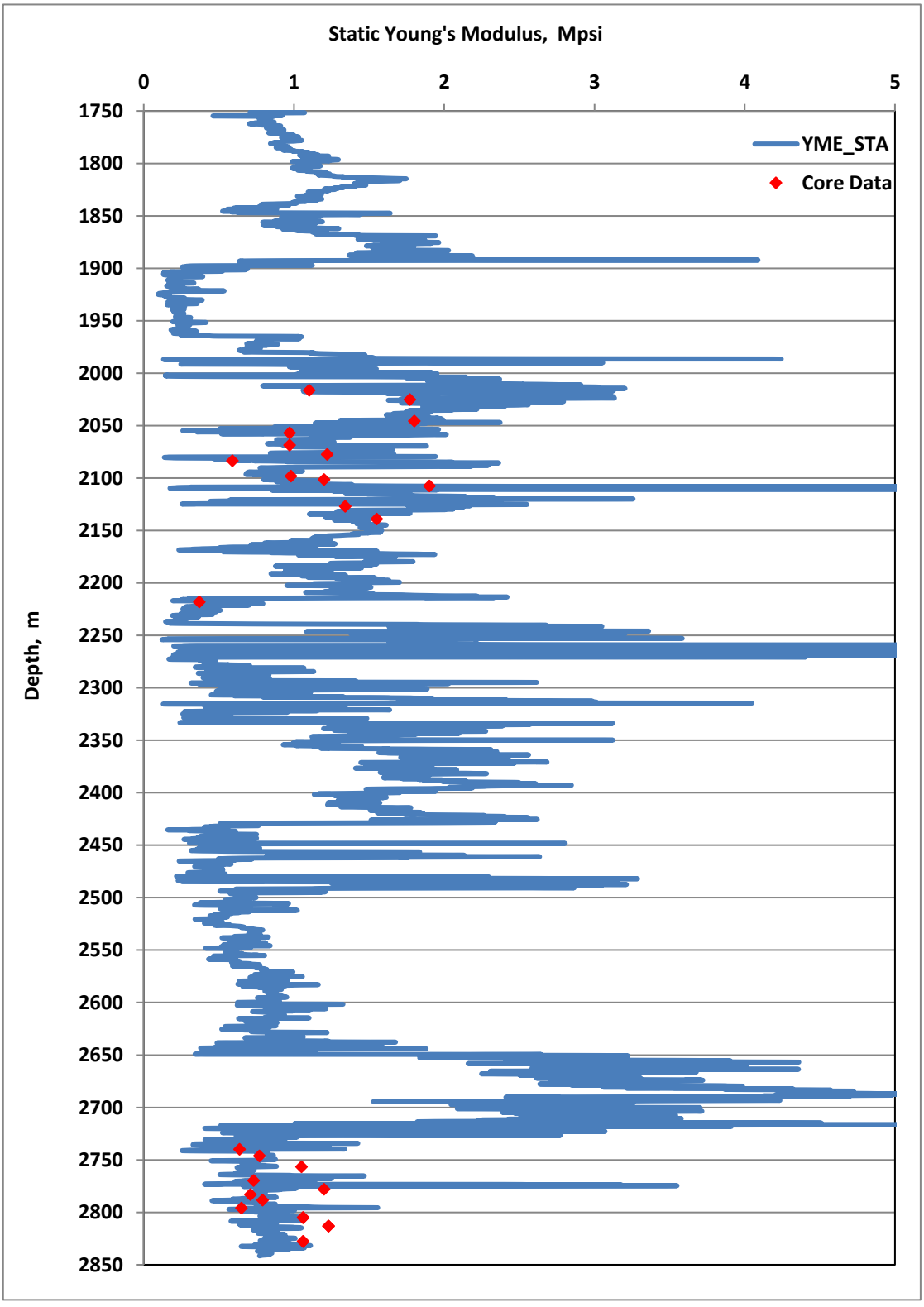

Figure 8. Static Young Modulus for well X3.

4.2 Determination of UCS

The un-confined compressive strength significantly affects wellbore stability because it is a vigorous player determining the failure criterion **(Allawi and Al-Jawad, 2021b)**. Therefore, compressive strength estimation should be accurate because it is the final word on the eventual calculations **(Xu et al., 2016)**. To get better results and avoid obstacles, several models have been investigated. **Table 2** shows these correlations with the results of statistical analysis (RMSE), where the results showed a significant difference between the Young Modulus correlation and other correlations, the reason is due to the dependence of the Young Modulus correlation on E_S and it is non- limitation by shally formations . After that the laboratory test data is compared with the results, as presented in **Figs. 9 to 12**.

Table 2. Various published correlations to calculate the UCS.

Equation for UCS	Reference	Root Mean Square Error (RMSE, psi)	Remarks
$UCS = 0.0866 * \frac{E_{dyn}}{C_{dyn}}[0.008V_{sh} + 0.0045(1 - V_{sh})]$	**(Coates Denoo, 1963)**	1767.545201	
$UCS = 1200e^{(-0.036\Delta t_c)}$	**(McNally, 1987)**	6021.376747	Australia
$UCS = 1.4138 * 10^7 {\Delta t_c}^{-3}$	**(McNally, 1987)**	765.875069	Gulf Coast
$UCS = 254(1 - 2.8\emptyset)^2$	**(Vernik et al., 1993)**	5847.594145	
$UCS = (2.28 + 4.1089E_s) * 145.037$	**(Bradford et al., 1998)**	229.3667259	
$UCS = (4.242 + E_s) * 145.037$	**(Yme, 2002)**	53.23181247	
$UCS = (46.2e^{0.0247E_s}) * 145.037$	**(Moos et al., 2003)**	4757.76922	
$UCS = 0.9616{\Delta t_c}^2 - 136.5\Delta t_c + 5002$	**(Novel et al., 2021)**	164965.9605	Shale Gas, Lithology neglecting
$UCS = 0.2686{\Delta t_c}^2 - 50\Delta t_c + 2339$	**(Novel et al., 2021)**	14967.9491	Shale Gas, Lithology considering
Where: $C_{dyn} = \frac{1}{K_{dyn}}$ $UCS = psi\ ; E_s = GPa\ ; \Delta t_c = us/ft\ ; E_{dyn} = psi\ ; K_{dyn} = psi$			

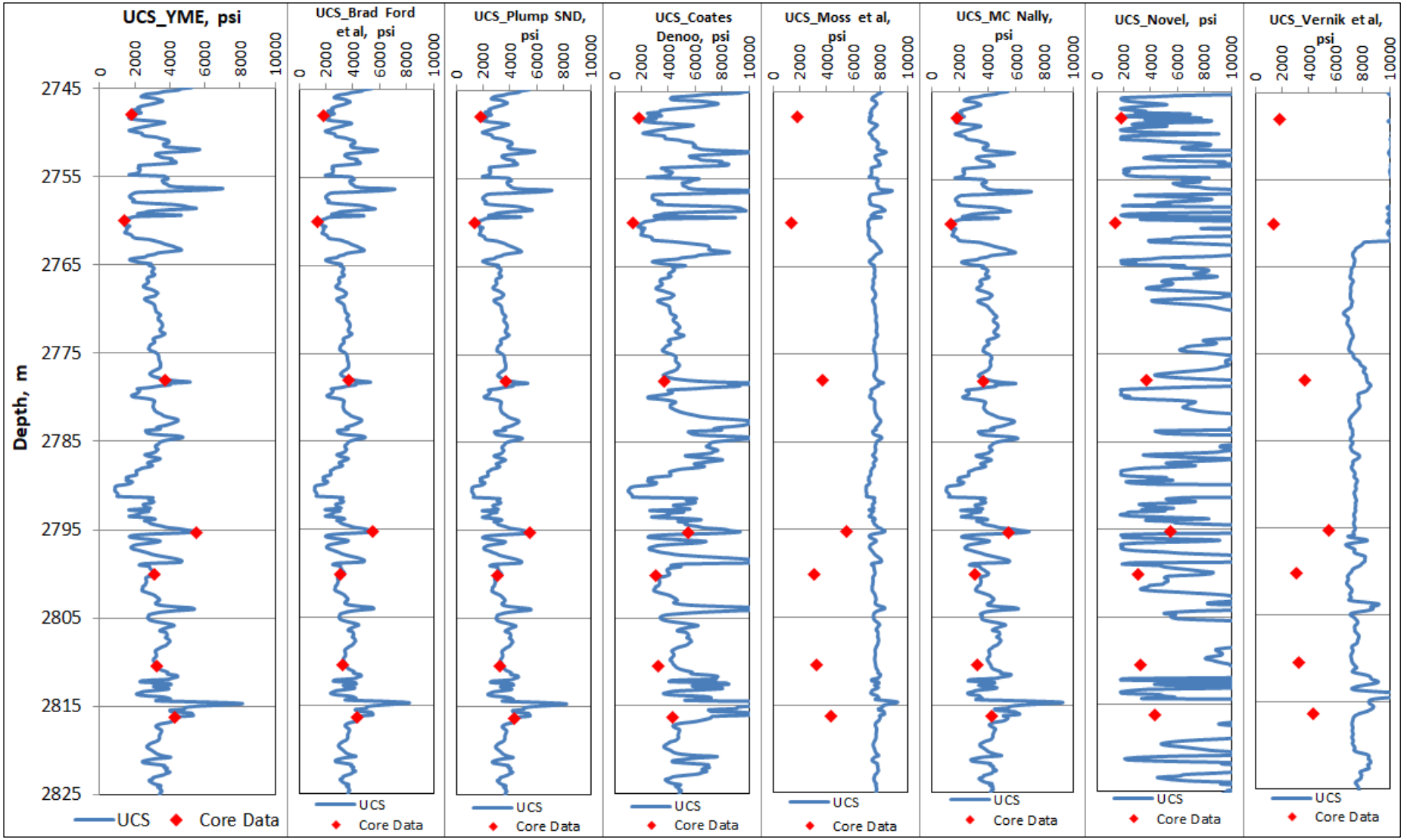

Figure 9. Unconfined compressive strength zmeasured by several methods for well X1.

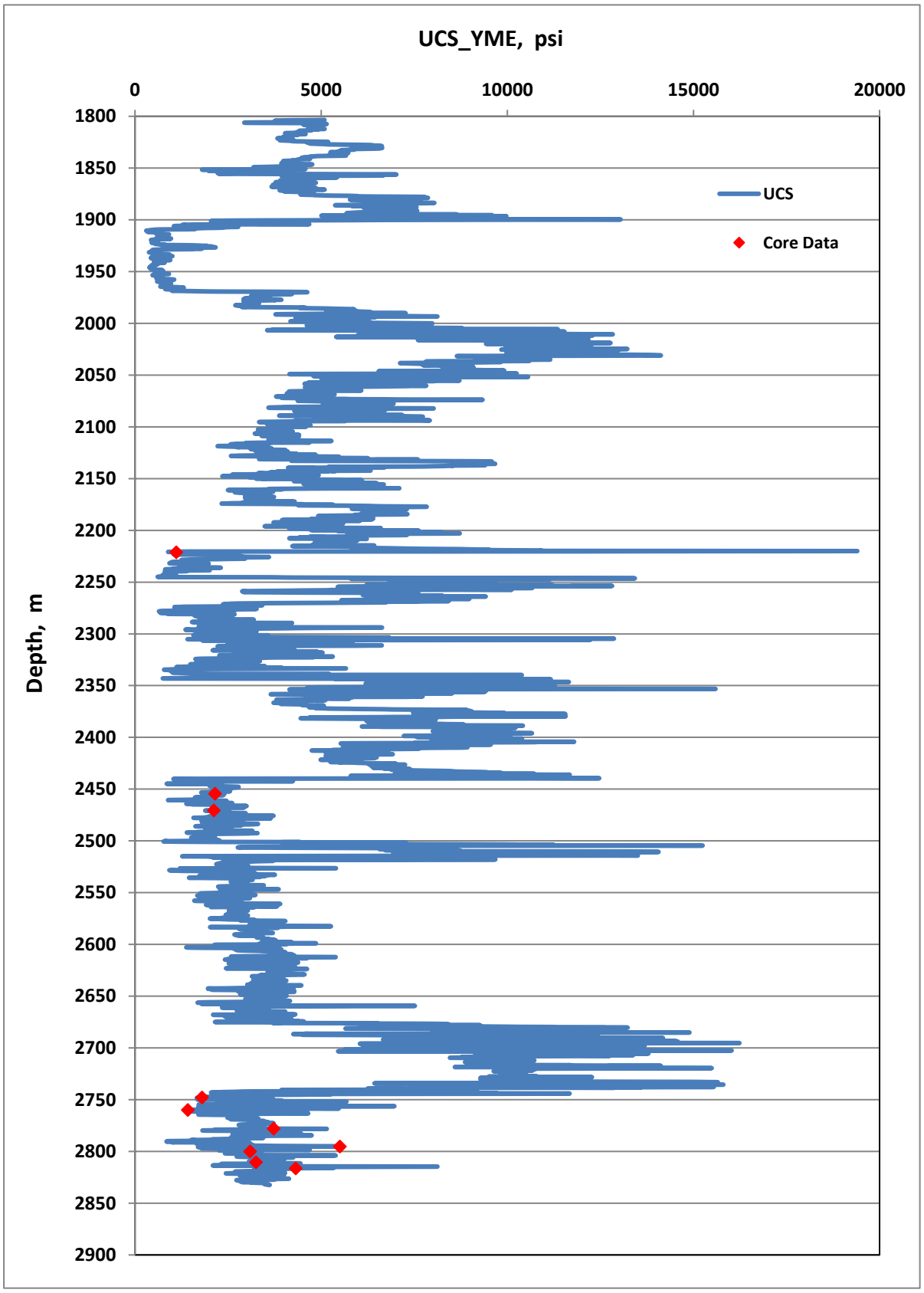

Figure 10. UCS for well X1.

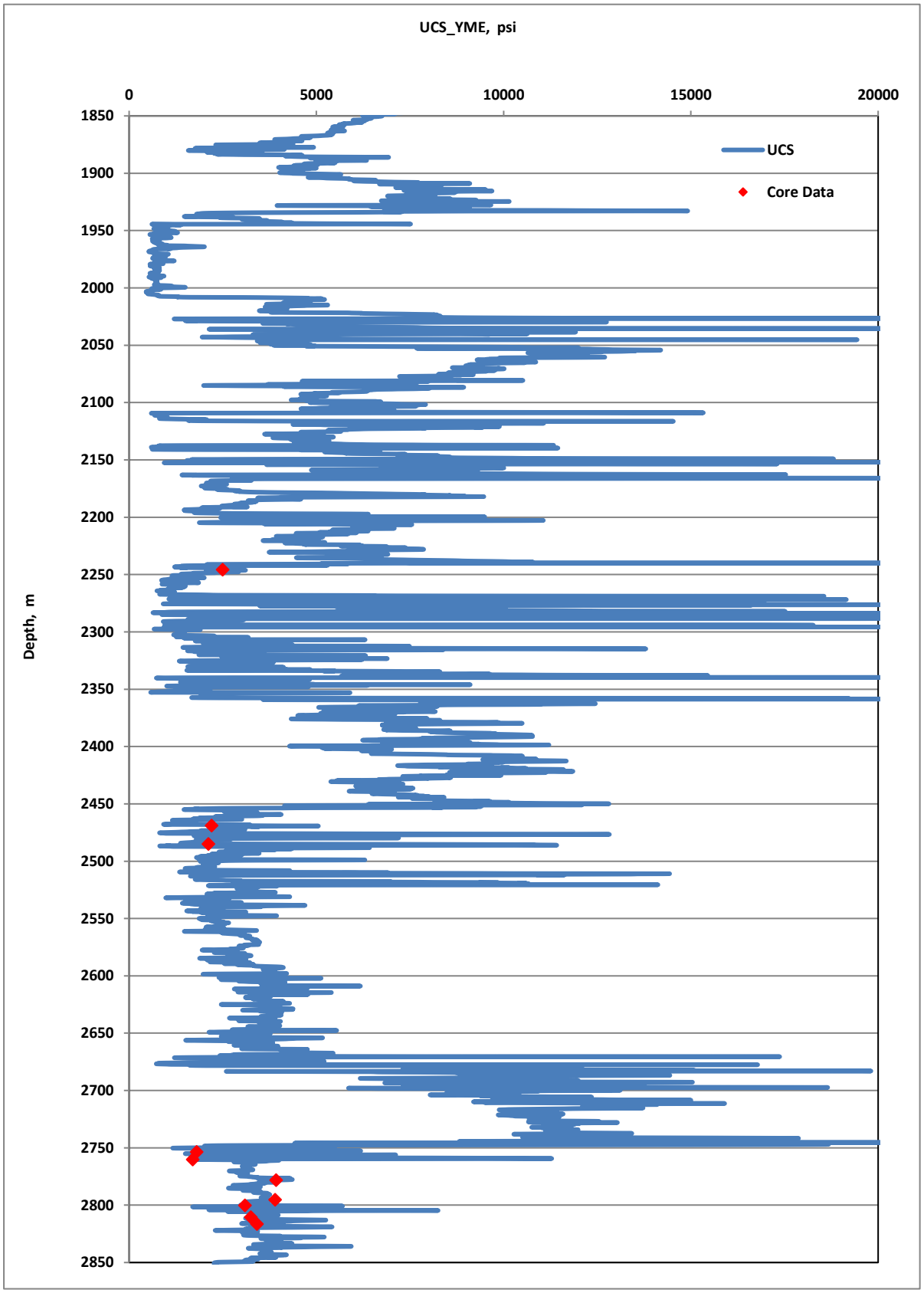

Figure 11. UCS for well X2.

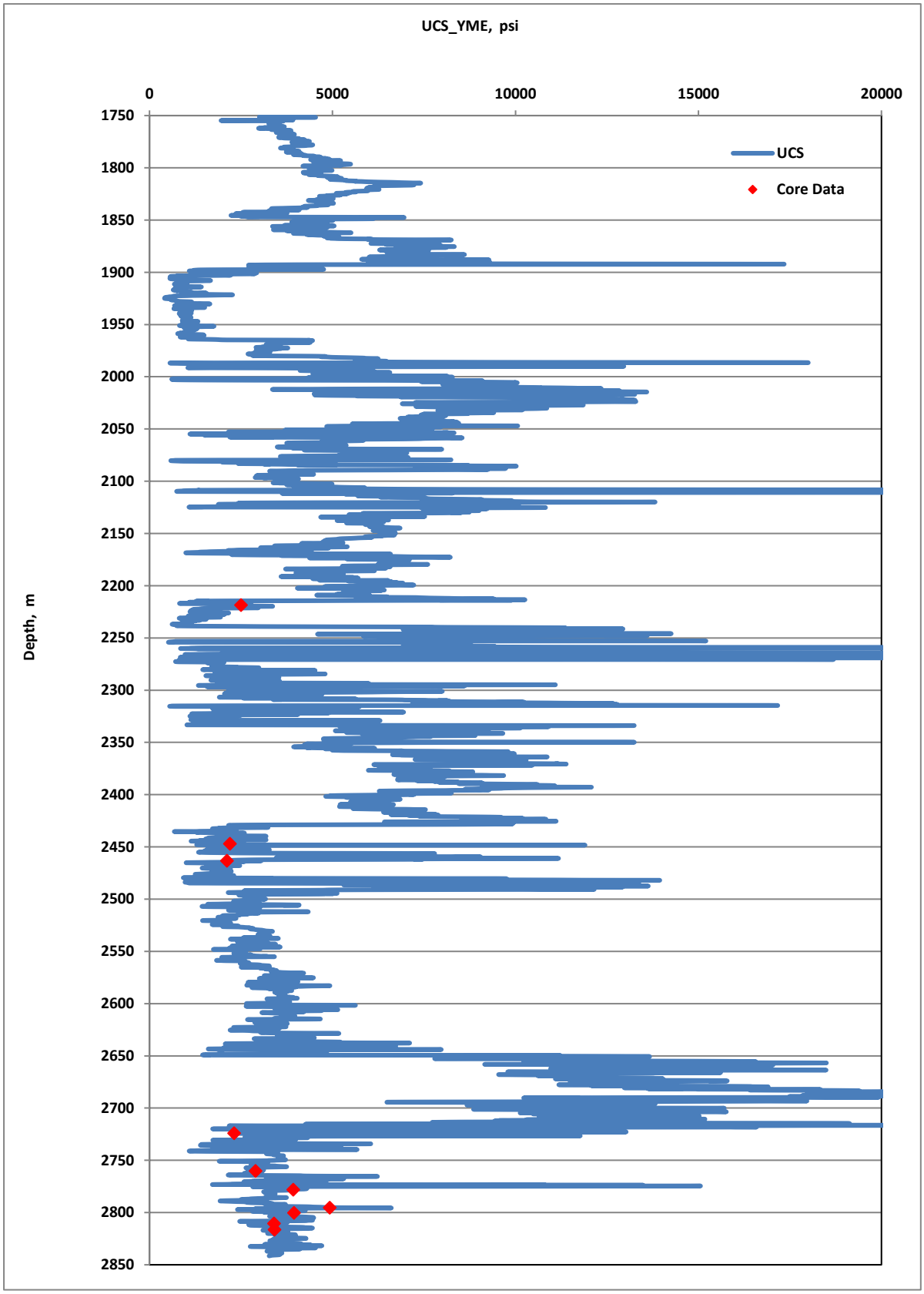

Figure 12. UCS for well X3.

5. STATISTICAL ANALYSIS

Statistical analysis was used to assess the correctness of the projected rock mechanical characteristics based on the empirical correlations described above **(Table 3)**. **Fig. 13** depicts the estimated values' root mean square error (RMSE) versus laboratory data.
The RMSE was calculated using **Eq. 5**.

$$RMSE = \sqrt{\frac{\sum(x_i - y_i)^2}{n}} \quad (5)$$

where:

Xi is the core-measured value, yi is estimated value, and n is the number of core-measured values.

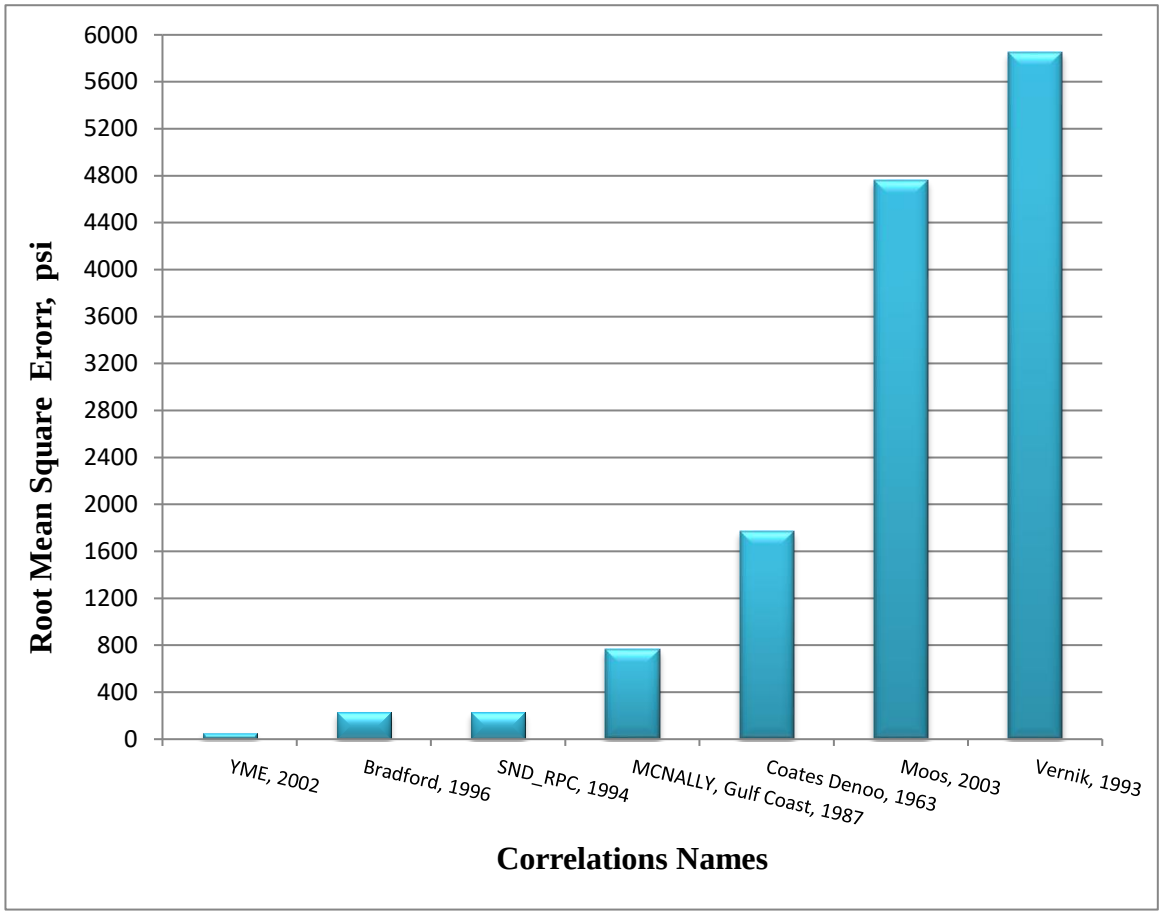

Figure 13. Comparison between results of unconfined compressive strength by different correlations.

Fig. 13 explains that (YME, 2002) gives the least error percentage, and then (Bradford, 1998, SND_RPC) comes, and then (McNally, 1987, Coates Denoo, 1963). While the error percentage increases when the (Moos, 2003, Vernik, 1993) correlations are used.

5. CONCLUSIONS

This work investigates the application of correlations between petrophysical and mechanical properties using wireline log data. The empirical relationships between UCS and E_S with E_d and V_P that previous authors reported were compared with the obtained data. Below are the main conclusions extracted from the discussed results.

- The John Fuller equation (Eq. 2) used to estimate Young's Modulus showed a good match with core tests, so it is recommended to use it in the fields of southern Iraq.
- Estimate the UCS depends on the E_S gives a closer prediction from the actual, contrary to the use of E_d,Δt_c,$\emptyset$, which gives incorrect results.
- The Novel 2021 correlation must be excluded from estimating the UCS because of the large difference between the predicted UCS and core data because this correlation was formulated for shale gas.
- Calculating the UCS based on Young Modulus 2002 correlation in Southern Iraqi fields is recommended. The reason is that this correlation gives a close value to laboratory data (RMSE=53.23psi) regardless of the diversity of the lithology of the section studied from Sadi to Zubair.

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NOMENCLATURE

Symbol	Description	Symbol	Description
E_d	= dynamic Young Modulus, psi.	UCS	= Unconfined compressive strength, psi.
E_S	= static Young Modulus, psi.	$\emptyset$	= Porosity, fraction.
G_{dyn}	= Shear modulus, psi.	Δt_s	= Shear slowness, us/ft.
INOC	= Iraqi national oil company.	Δt_c	= Compressional slowness, us/ft.
K_{dyn}	= Bulk modulus, psi.	ρ	= Bulk density, gm/cc
RMSE	= Root mean square error		

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